JOURNAL OF APPLIED PHYSICS VOLUME 85, NUMBER 8 15 APRIL 1999

An experimental study of light modulator using magnetic fluid

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A type of light modulator using light-absorbing magnetic fluid has been studied experimentally. The basic operation principle and design of the modulator are addressed. It is shown that the luminance of the device can be modulated by applying a moderate level of electric current to a light-reflecting metal electrode. A high contrast ratio comparable to that of printed material was obtained using a kerosene-base magnetite magnetic fluid with a saturation magnetization of 196 G and a thickness of around 20 μm. Doubling of the luminance from a minimum level takes about 200 ms for a driving current of 80 mA. The operation speed of the cell was found to increase almost exponentially with driving current, suggesting the possibility of motion picture applications. © *1999 American Institute of Physics.* [S0021-8979(99)43408-5]

I. INTRODUCTION

Magnetic fluid is a stable colloidal dispersion of ferromagnetic particles in a liquid carrier,[1] and it is normally a good contrasting medium carrying a deep dark color due to its high light absorbance.[2] When a magnetic fluid is subjected to a magnetic field, it acquires a magnetic moment and easily deforms its shape. These properties make the material suitable for application in the display device area.[3–5]

In this article an experimental study on a type of light modulator using magnetic fluid is presented. The operation principle of the modulator is described, and the design consideration to obtain a high contrast ratio and a high operation speed is discussed. A structure using zigzagged electrode patterns and a thin film of magnetic fluid covering the surface of the cell is proposed. Experimental results obtained using a test cell are reported.

II. PRINCIPLE OF OPERATION

The basic structure of the magnetic fluid light modulator consists of electrodes patterned on a dielectric substrate as shown in Fig. 1 and a thin film of light-absorbing magnetic fluid covering the surface of the sample. The luminance of a cell is determined by its surface reflectivity, and the reflectivity is determined by the thickness of the fluid. Initially, a cell is at a dark state because most of the incident light from the front face of the cell is absorbed by the fluid. When an electrical current is applied to electrode (I) in Fig. 1, the thickness of the fluid over the electrode becomes thinner by the field-induced magnetic force as will be discussed below, resulting in a higher luminance because less light is absorbed in the fluid.

The equation of motion for an irrotational flow of an incompressible magnetic liquid is given by[1,6]

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\boldsymbol{\nabla}\mathbf{v}\right)=-\nabla p+\rho\mathbf{g}+\mu_0 M\nabla H, \qquad (1)$$

where $\mathbf{v}$, ρ, and M are the velocity, density, and magnetization of the liquid, respectively, p is the pressure, $\mathbf{g}$ is the gravitational acceleration, μ_0 is the free-space permeability, and H is the magnetic-field intensity. As the last term in the right-hand side of Eq. (1) implies, the magnetic force is proportional to the field gradient. The horizontal component (parallel to the sample surface) of the magnetic force in the outside of the electrode region tends to pull the fluid into the electrode region. On the other hand, the vertical component (perpendicular to the sample surface) of the magnetic force pushes down the fluid toward the sample surface like the gravitational force. However, since the fluid is almost incompressible, the force tends to push the fluid out of the electrode region. Therefore, if the vertical component dominates the horizontal counterpart, the fluid will be depleted from the middle of the electrode region.

Obviously, it is required to have a magnetic field with a larger vertical gradient compared to the horizontal gradient, and a zigzagged electrode is an effective choice to get such a field profile. Since the magnetic fields produced by the currents in opposite directions cancel each other, the field intensity decreases rapidly as the altitude increases, whereas it changes slightly in the lateral direction. Figure 2 shows the distribution of the field gradients at 5 μm above the substrate surface. The magnetic field was calculated assuming a relative permeability of 2 for the magnetic fluid, and the distri-

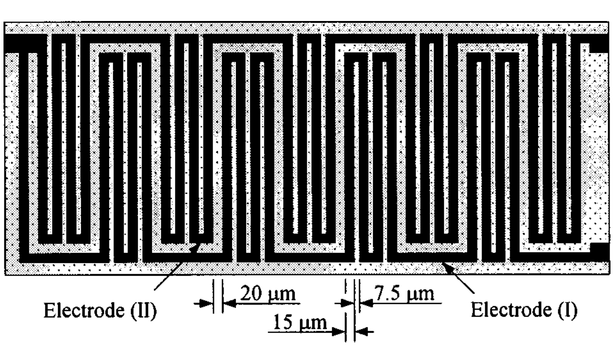

FIG. 1. Schematic diagram of the magnetic fluid light modulator cell.

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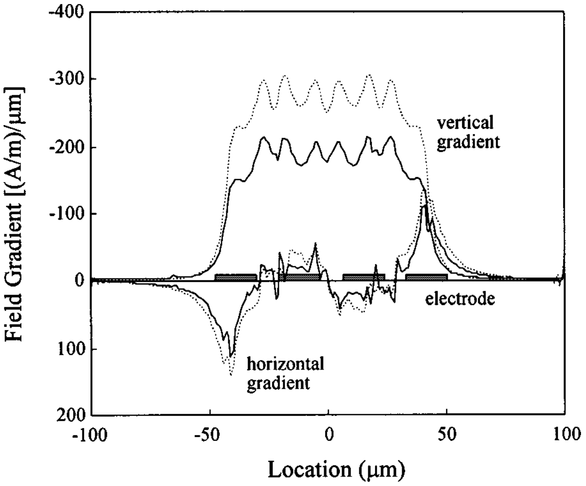

FIG. 2. Distribution of magnetic-field gradients at 5 μm above the substrate surface with (solid lines) and without (dotted lines) magnetic fluid for a driving current of 80 mA.

bution without the fluid is also shown for comparison. Consequently, a modulation of cell luminance corresponding to a desired brightness can be achieved. Meanwhile, the recovering of the dark state can be obtained by the capillary action of the fluid, or it can be accelerated by applying a current into electrode (II).

III. EXPERIMENT

Test cells with electrode patterns with a thickness of 0.7 μm and a width/space of 15 μm/7.5 μm were fabricated on a surface-oxidized silicon wafer through thermal evaporation and dry etching of aluminum. A 3 μm thick oxide layer was then deposited to provide a gap between the electrode and the magnetic fluid. A thin film of magnetic fluid with a thickness of around 20 μm was coated on the surface of the cell using a plastic blade. The prepared wafer was finally mounted on a sample holder for the application of the electrical signal. The area of the cell was $1.5\times0.5\,\mathrm{mm}^2$.

Considering the dynamics of the liquid film flow, it is required for the magnetic fluid to have a low viscosity, a low density, and a high saturation magnetization for a high speed of operation.[1] A high saturation magnetization is also preferable to achieve a high contrast ratio because it is normally obtained by increasing the concentration of light-absorbing magnetic particles. A kerosene-base magnetite magnetic fluid was prepared for the study. The saturation magnetization, viscosity, and density of the fluid were measured to be 196 G, 3.09 cP s, and 1.01 g/cm^3, respectively, using an LDJ 9600 vibrating sample magnetometer (VSM).

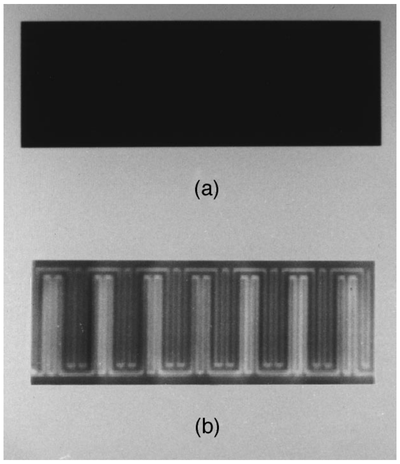

FIG. 3. Captured images of the magnetic fluid light modulator (a) before and (b) after the application of a driving current.

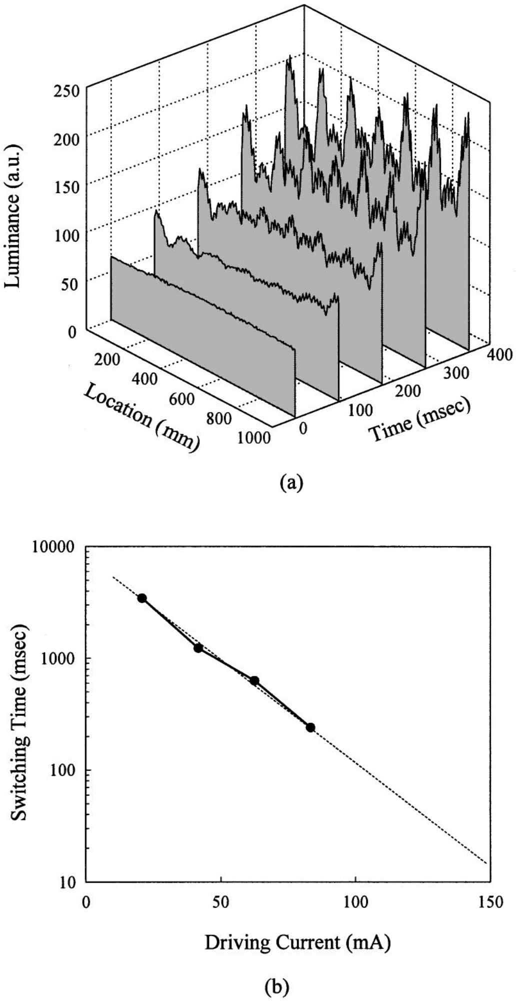

FIG. 4. (a) Luminance vs time for $I=80\,\mathrm{mA}$ and (b) switching time vs driving current for the magnetic fluid light modulator.

The variation of the surface brightness of the sample, which is mounted on a microscope-equiped probe station, upon the application of a current pulse was measured using a charge-coupled device camera and a frame grabber. Since the frame rate (30 fps) of the composite video signal from the camera was not high enough to capture fast-changing images, low-amplitude current pulses were used to drive the cell. Figures 3(a) and 3(b) show the captured images of the cell before and after the application of the current pulse, respectively.

IV. RESULTS AND DISCUSSION

It can be seen from Fig. 3 that the magnetic fluid initially placed on electrode (I) was pushed away from the region by the current-induced field. The variation of the cell luminance upon the application of a current of 80 mA into electrode (I) is plotted versus time in Fig. 4(a). It can be seen from Fig. 4(a) that the luminance increases from an initial level determined mainly by the reflection of the incident light at the fluid surface. Figure 4(b) shows the dependence of the switching speed on the driving current. The switching time is defined as the time required to double the luminance level averaged across the electrode (I) region from its initial value, and it was found to decrease almost exponentially with the driving current. The doubling of the luminance level takes about 200 ms for a driving current of 80 mA, whereas it takes about 2500 ms for a current of 20 mA.

It can be speculated based on the current dependence of the switching time shown in Fig. 4(b) that an operation speed required to accommodate motion picture applications is achievable using a moderately high current. Although the measurement was made up to a current of 80 mA, where the heat dissipation by the electrode began to disturb the cell operation, a higher current drive is possible by using thicker electrodes preferably with a higher conductivity. Considering the structure and operation principle of the light modulator proposed in this article, a further improvement of the contrast ratio as well as the operation speed is also conceivable by using a magnetic fluid with a high saturation magnetization and a low viscosity.

A flat-panel display device can be implemented by building a two-dimensional array of the modulator cells. Control of the thickness for the magnetic fluid film can be achieved by forming supporters for the liquid on the substrate. Meanwhile, it can be noticed from Fig. 3(b) that the thickness of the magnetic fluid film on the inactive electrode (II) was also changed significantly by the current in the active electrode (I). The thickness variation in the region is believed to be due mainly to the poor localization of the magnetic field. Since the field intensity remains considerably high even in the magnetic fluid on the neighboring inactive electrode, the design of the electrode is to be optimized to limit the field within a short range from the active electrode.

V. CONCLUSIONS

A type of light modulator using magnetic fluid has been studied experimentally. It is shown that the brightness of the cell can be modulated by applying a moderate amount of electric current. A contrast ratio comparable to that of a printed material was obtained using a magnetic fluid with a saturation magnetization of 196 G and a thickness of around 20 μm. The operation speed of the cell was found to increase almost exponentially with the driving current, and a switching time of 200 ms was achieved using a current of 80 mA. A faster operation will be available with a moderately higher current, suggesting the possibility of motion picture applications.

ACKNOWLEDGMENT

This work is supported by the Ministry of Information and Communication of the Republic of Korea.

[1] B. M. Berkovsky, V. F. Medvedev, and M. S. Krakov, *Magnetic Fluids Engineering and Applications* (Oxford University Press, Oxford, 1993).
[2] J. R. Harbour and M. L. Hair, Photograph. Sci. Eng. **26**, 30 (1982).
[3] E. E. Olah, U.S. Patent No. 3863249 (1975).
[4] R. A. Scranton and D. A. Thompson, IBM Tech. Discl. Bull. **20**, 2036 (1977).
[5] K. Myazawa, Patent No. EP 0633488A1 (1994).
[6] R. E. Rosensweig, *Ferrohydrodynamics* (Dover, New York, 1997).